Higgs decays to invisible modes at the LHC and ILC

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Outline

Motivation

Invisible Higgs at the LHC
Interlude: Invisible Higgs at the Tevatron?

Invisible Higgs at the ILC

Comparison
Future directions

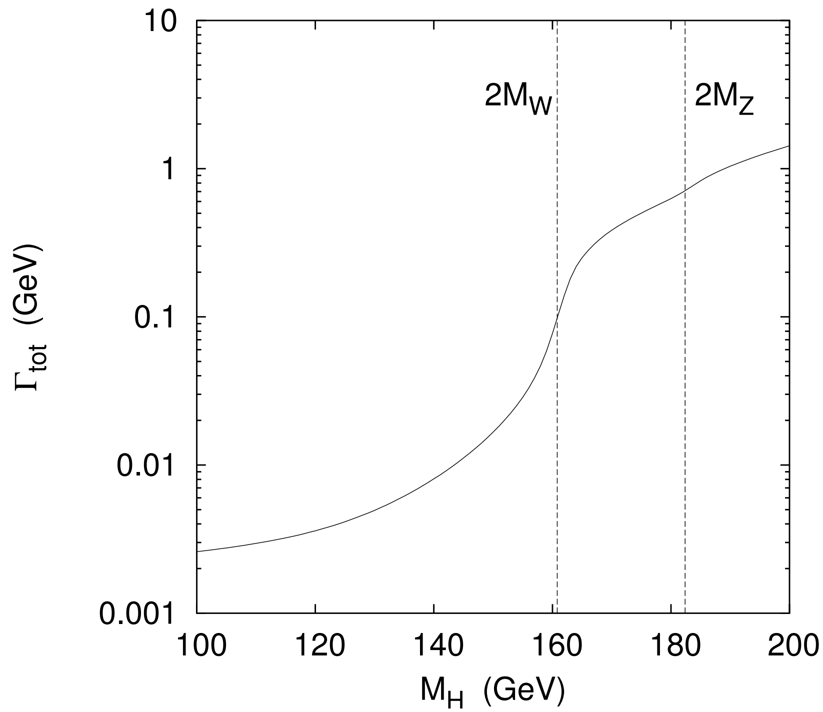
Motivation

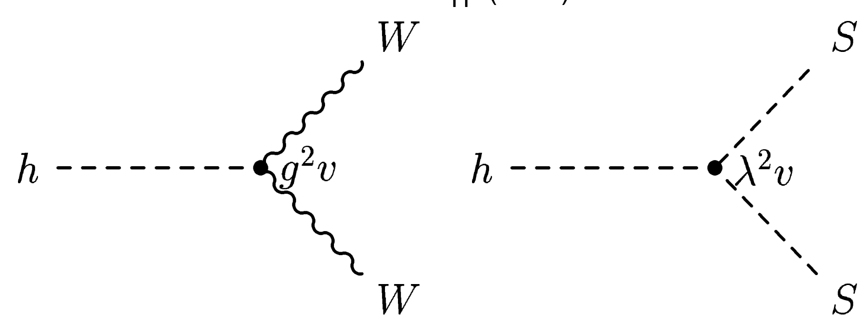
SM Higgs is very narrow for $m_H \lesssim 160$ GeV.

Any new decay mode with reasonable partial width can easily become the dominant BR.

If there is a neutral (quasi)stable particle with mass $< m_H/2$ and EW-strength coupling to H, then $H \rightarrow$ invisible can be the dominant decay.

- $H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $H \rightarrow SS$, scalar dark matter
- $H \rightarrow$ KK neutrinos in EDim
- $H \rightarrow$ Majorons
- etc.

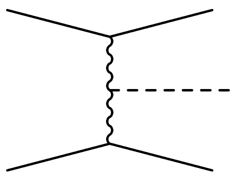




Invisible Higgs at LHC

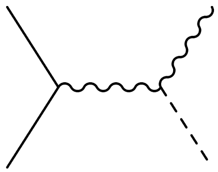
VBF $\rightarrow$ H_{inv} [Eboli & Zeppenfeld (2000); Neukermans & Di Girolamo (2003)]

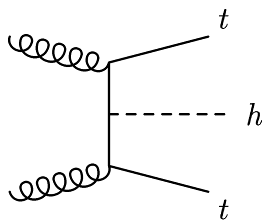
Signal is $jj\not{p}_T$; jets are hard and forward



$Z+H_{\text{inv}}$ [Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003); Davoudiasl, Han & H.L. (2004); Meisel, Dührssen, Heldmann & Jakobs (2006)]

Signal is $\ell^+\ell^-\not{p}_T$, with $m(\ell^+\ell^-) = m_Z$ $(\ell = e, \mu)$

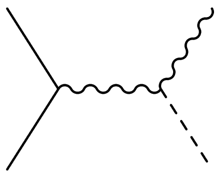




$t\bar{t}H_{\text{inv}}$ [Gunion (1994); Kersevan, Malawski & Richter-Was (2002)]

Signal is $bjj + b\ell + \not{p}_T$.

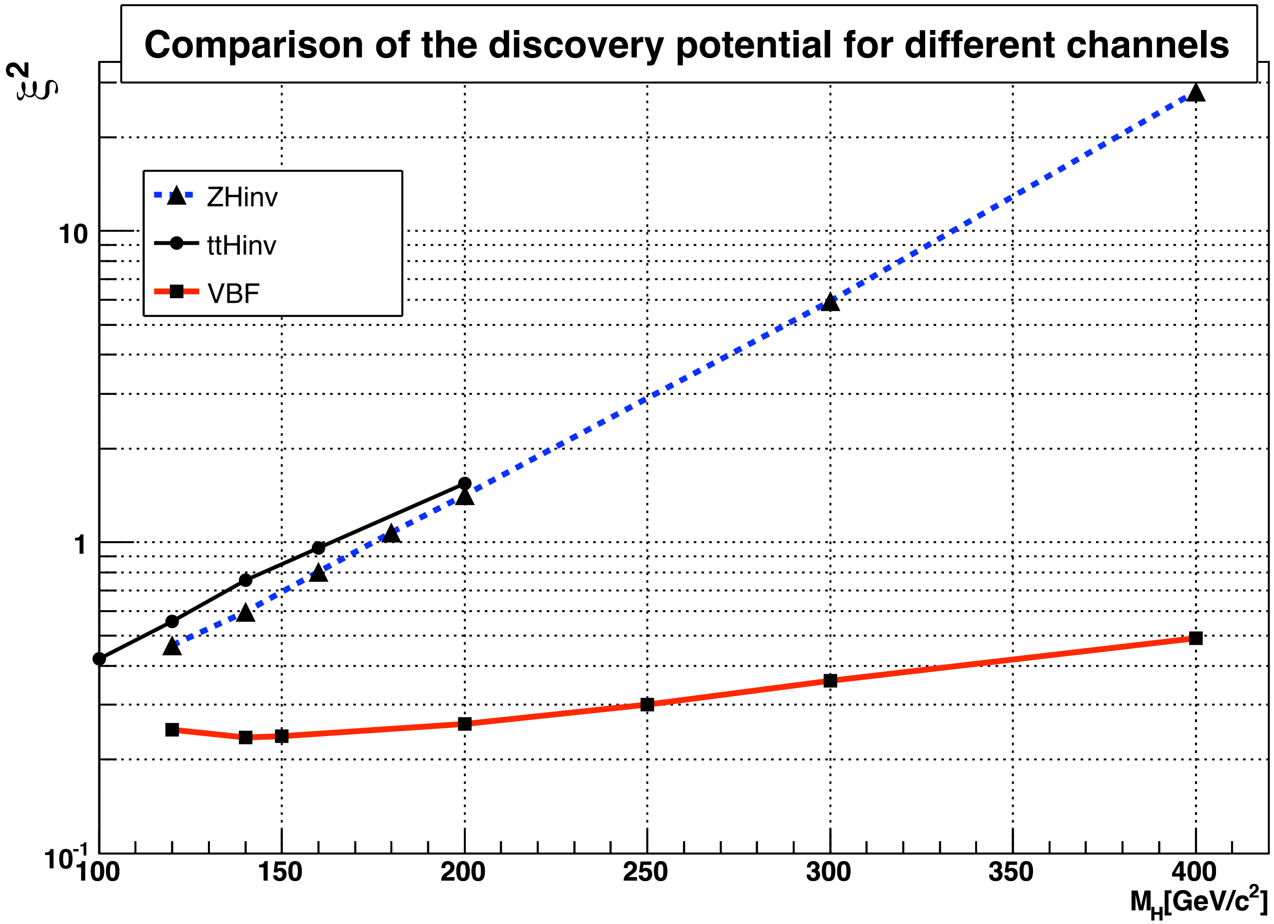
$W + H_{\text{inv}}$ [Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003)]



Signal is $\ell\not{p}_T$; totally swamped by background.

95% CL exclusion limits with 30 fb^{-1} at LHC

ξ^2 is a scaling factor: $\sigma \times \mathrm{BR}(H \to \mathrm{invis}) \equiv \xi^2 \sigma_{\mathrm{SM}}$



ZH_{inv} – uses $Z \to \ell^+\ell^-$

VBF looks very good, but not clear how well events can be triggered.

$t\bar{t}H_{\mathrm{inv}}$ – may be room for improvement? ATLAS study in progress.

[Plot from ATL-PHYS-PUB-2006-009]

Naive extrapolation from the ATLAS plot for 30 (300) fb^{-1}:

Value of ξ^2 excluded at 95% CL:

	$m_H = 120$ GeV	140 GeV	160 GeV
VBF $\to H_{\text{inv}}$	0.25 (0.08)	0.25 (0.08)	0.25 (0.08)
$Z + H_{\text{inv}}$	0.45 (0.15)	0.6 (0.2)	0.8 (0.25)
$t\bar{t}H_{\text{inv}}$	0.55 (0.17)	0.75 (0.25)	0.95 (0.3)

1σ uncertainty on $\sigma \times$ BR(inv) for $\xi^2 = 1$:

	$m_H = 120$ GeV	140 GeV	160 GeV
VBF $\to H_{\text{inv}}$	13% (4%)	13% (4%)	13% (4%)
$Z + H_{\text{inv}}$	23% (7%)	30% (10%)	40% (13%)
$t\bar{t}H_{\text{inv}}$	28% (9%)	38% (12%)	48% (15%)

Value of ξ^2 required for 5σ discovery:

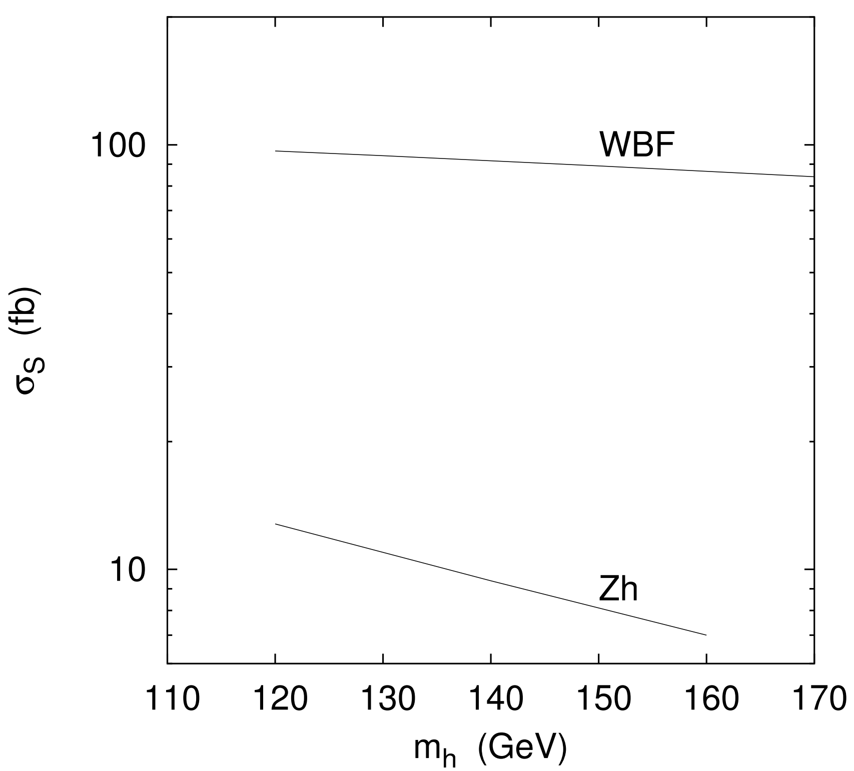
	$m_H = 120$ GeV	140 GeV	160 GeV
VBF $\to H_{\text{inv}}$	0.63 (0.2)	0.63 (0.2)	0.63 (0.2)
$Z + H_{\text{inv}}$	1.1 (0.36)	1.5 (0.47)	2.0 (0.63)
$t\bar{t}H_{\text{inv}}$	1.4 (0.43)	1.9 (0.59)	2.4 (0.75)

Caveat: 300 fb^{-1} numbers just scaled by $\mathcal{L}^{-1/2}$. Systematics, background normalization from data don't scale this way!

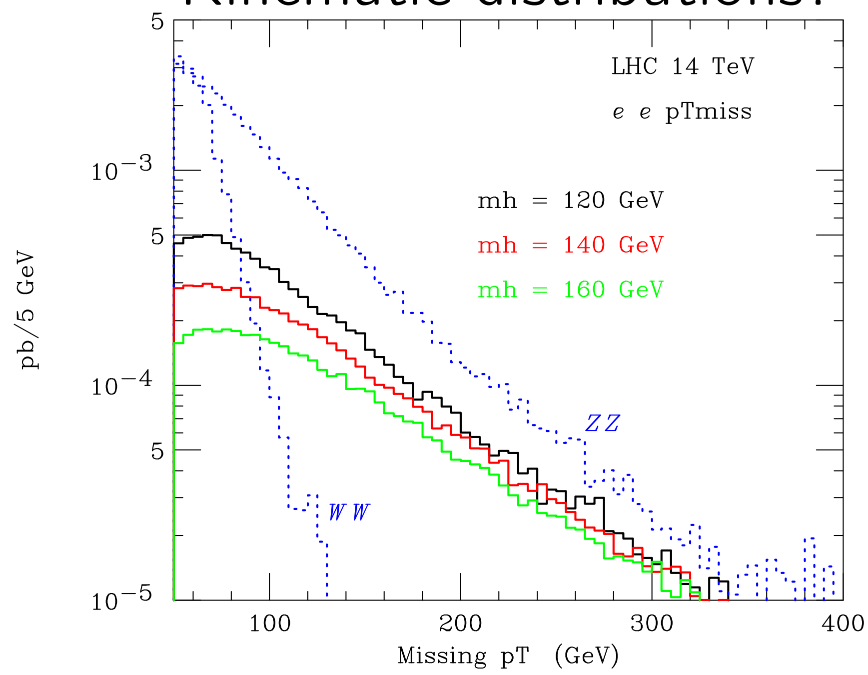
Higgs mass measurement from $H \to$ invisible

Mass of H_{inv} is accessible only through production process.

Cross section



Kinematic distributions?



(needs more work)

Davoudiasl, Han & H.L. (2004)

Signal rate depends on m_H. Will use VBF and $Z + H_{\text{inv}}$.
First pass: assume $\xi^2 = 1$.

Higgs mass determination from $Z + H_{\text{inv}}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$(d\sigma_S/dm_h)/\sigma_S$ (1/GeV)	−0.013	−0.015	−0.017
Statistical uncert.	21% (6.6%)	28% (8.8%)	37% (12%)
Background normalization uncert.	33% (10%)	45% (14%)	60% (19%)
Total uncert.	40% (16%)	53% (19%)	71% (24%)
Δm_h (GeV)	30 (12)	35 (12)	41 (14)

Davoudiasl, Han & H.L. (2004)

$Z+H_{\text{inv}}$: $\Delta m_H = 30/35/41\ (12/12/14)$ GeV with 10(100) fb^{-1}

Higgs mass determination from VBF$\rightarrow H_{\text{inv}}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	130	150	200
$(d\sigma_S/dm_h)/\sigma_S$ (GeV^{-1})	−0.0026	−0.0026	−0.0028	−0.0029
Statistical uncert.	5.3% (1.7%)	5.4% (1.7%)	5.7% (1.8%)	6.4% (2.0%)
Background norm.	5.2% (2.1%)	5.3% (2.1%)	5.6% (2.2%)	6.5% (2.6%)
Total uncert.	11% (8.6%)	11% (8.6%)	11% (8.6%)	12% (8.8%)
Δm_h (GeV)	42 (32)	42 (33)	41 (31)	42 (30)

Davoudiasl, Han & H.L. (2004)

VBF: $\Delta m_H \simeq 42\ (32)$ GeV with 10 (100) fb^{-1}

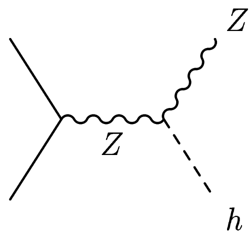
$Z + H_{\text{inv}}$ cross section falls faster with m_H than VBF:
more m_H dependence but less statistics.

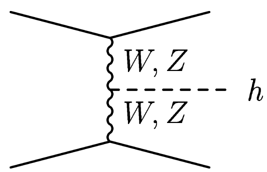
All numbers used here are from theorist parton-level MC studies.

Getting m_H from one cross section relies on assumption $\xi^2 = 1$.

Second pass: use ratio of $Z + H_{\rm inv}$ and VBF rates.

$Z + H_{\rm inv} \sim HZZ$ coupling; VBF $\sim HWW$, HZZ couplings: related by custodial SU(2) in models with only Higgs doublets/singlets.





Example: MSSM or 2HDM

ZZH coup $= (g m_Z / \cos\theta_W) \sin(\beta - \alpha)$

WWH coup $= g m_W \sin(\beta - \alpha)$

Higgs mass determination from ratio method with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$r = \sigma_S(Zh)/\sigma_S(\text{WBF})$	0.132	0.102	0.0807
$(dr/dm_h)/r$ (1/GeV)	-0.011	-0.013	-0.013
Total uncert., $\Delta r/r$	41% (16%)	54% (20%)	72% (25%)
Δm_h (GeV)	36 (14)	43 (16)	53 (18)

Davoudiasl, Han & H.L. (2004)

Ratio method:

$\Delta m_H = 36/43/53\ (14/16/18)$ GeV with 10 (100) fb^{-1}

Assumed $\xi^2 = 1$ for signal statistics.

Summary of m_H extraction 1σ uncertainty with 100 fb^{-1}:

	$m_H = 120$ GeV	140 GeV	160 GeV
$Z + H_{\text{inv}}$, $\xi^2 = 1$	12 GeV	12 GeV	14 GeV
VBF, $\xi^2 = 1$	32 GeV	32 GeV	31 GeV
Ratio method	14 GeV	16 GeV	18 GeV

Comments:

- All numbers used come from theorist parton-level MC studies.

- VBF numbers are from Eboli & Zeppenfeld and include a central jet veto – this degrades at higher luminosity LHC running.

- Precisions do not scale with $\mathcal{L}^{-1/2}$ because of systematics and background normalization from data.

- With $Z + H_{\text{inv}}$, VBF, and $t\bar{t}H_{\text{inv}}$ channels, together with assumption of Higgs doublets/singlets only, we should be able to simultaneously fit for m_H, ξ_V, and g^2_{Htt}/g^2_{HVV}.

Interlude: Invisible Higgs at the Tevatron?

Pheno studies for $m_H = 120$ GeV:

$Z + H_{\text{inv}}$ [Martin & Wells, hep-ph/9903259]

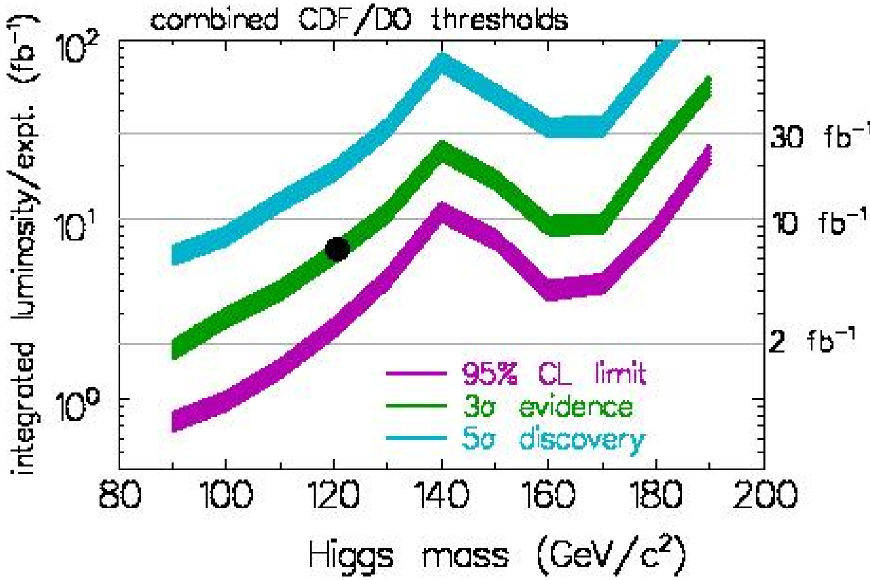
- 1.9σ with 10 fb^{-1}
- 3σ requires 12 fb$^{-1} \times 2$ detectors

VBF$\rightarrow H_{\text{inv}}$ [Davoudiasl, Han, & H.L., hep-ph/0412269]

- 1.6σ with 10 fb^{-1}
- 3σ requires 18 fb$^{-1} \times 2$ detectors
- No central jet veto used: room for improvement.

Combining these 2 channels:
3σ requires 7 $\mathrm{fb}^{-1} \times 2$ detectors.

Comparable to SM Higgs sensitivity?



$m_H = 120$ GeV: above LEP limit.
Could extend LEP exclusion before LHC data is analyzed.

No central jet veto used: room for improvement.

LHC: central jet veto improves S/B by factor of 3

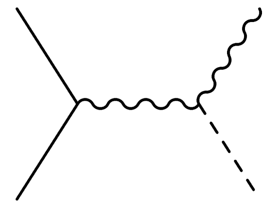
[Rainwater, hep-ph/9908378; Eboli & Zeppenfeld, hep-ph/0009158]

If central jet veto works this well for Tevatron, can get 3σ in VBF channel alone with 6 $\mathrm{fb}^{-1} \times 2$ detectors.

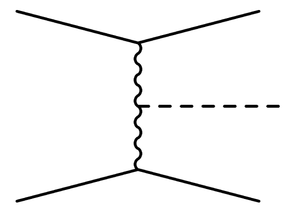
Invisible Higgs at ILC

Relevant production modes:

$e^+e^- \to ZH$



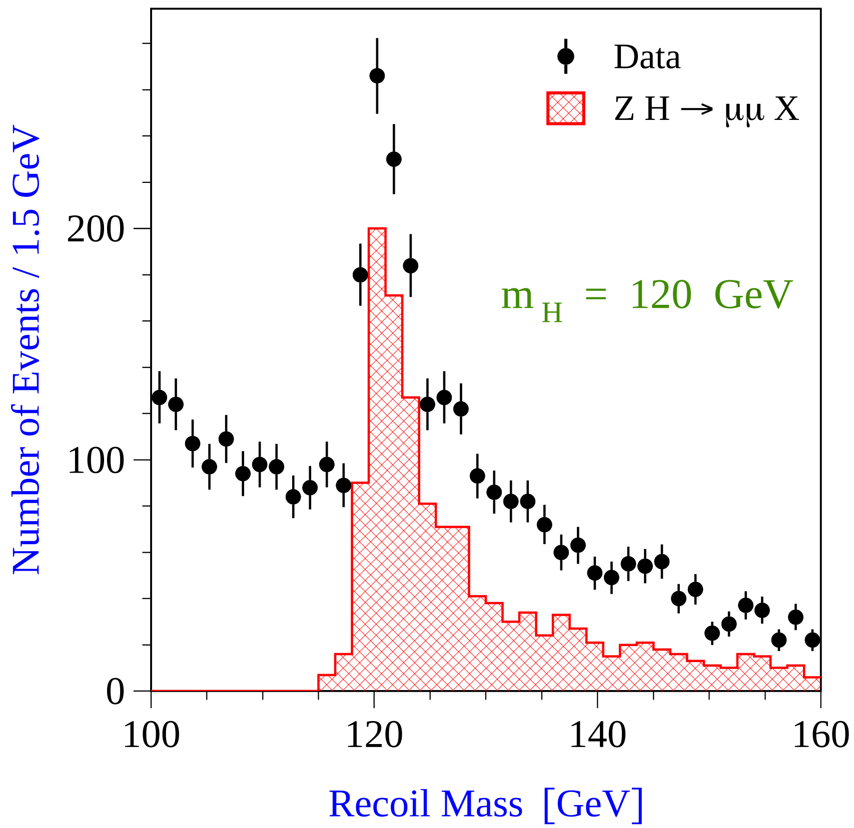
$e^+e^- \to e^+e^-H$
(ZZ fusion)



$e^+e^- \to \nu\bar{\nu}H$ – invisible for $H_{\rm inv}$

$e^+e^- \to t\bar{t}H$ – cross section too small at 500 GeV

Use recoil mass technique to find (missing) mass bump.



[TESLA TDR] $m_H = 120$ GeV, $\sqrt{s} = 350$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, $\mu\mu$ only

Measure m_H and $e^+e^- \to ZH$ total cross section.

Study: search for $e^+e^- \to ZH_{\text{inv}}$ with $Z \to q\bar{q}$.

[M. Schumacher, LC-PHSM-2003-096]

First discover H and measure mass (via recoil mass?)
Measure total $e^+e^- \to ZH$ cross section from recoil technique.

Then look at $e^+e^- \to ZH_{\text{inv}}$ with $Z \to q\bar{q}$.

- Force event to 2 jets

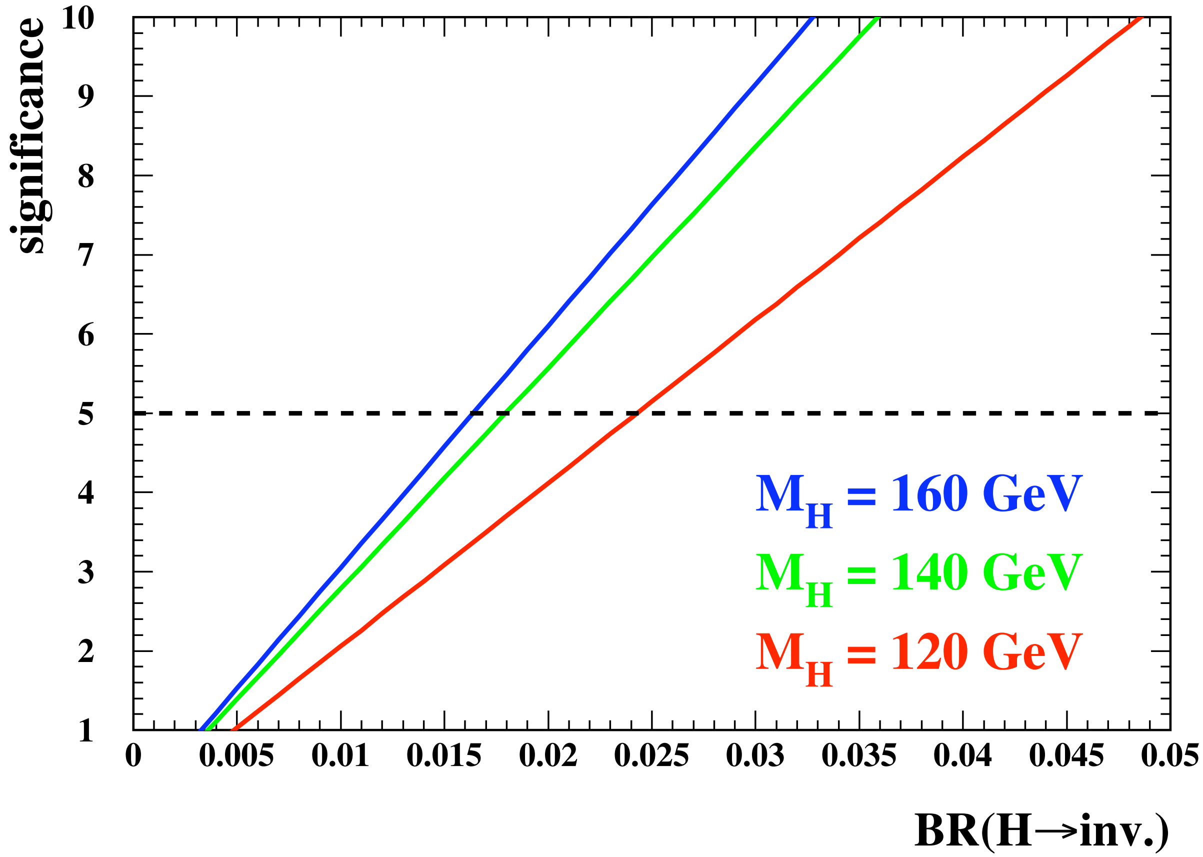
- Cuts on E_{vis}, p_T^{tot}, $\cos\theta_{\text{dijet}}$

- Require jj reconstruct Z mass: $|M_{\text{vis}} - M_Z| < 7.5$ GeV

- Require missing mass near H mass: $|M_{\text{miss}} - M_H| < 15$ GeV

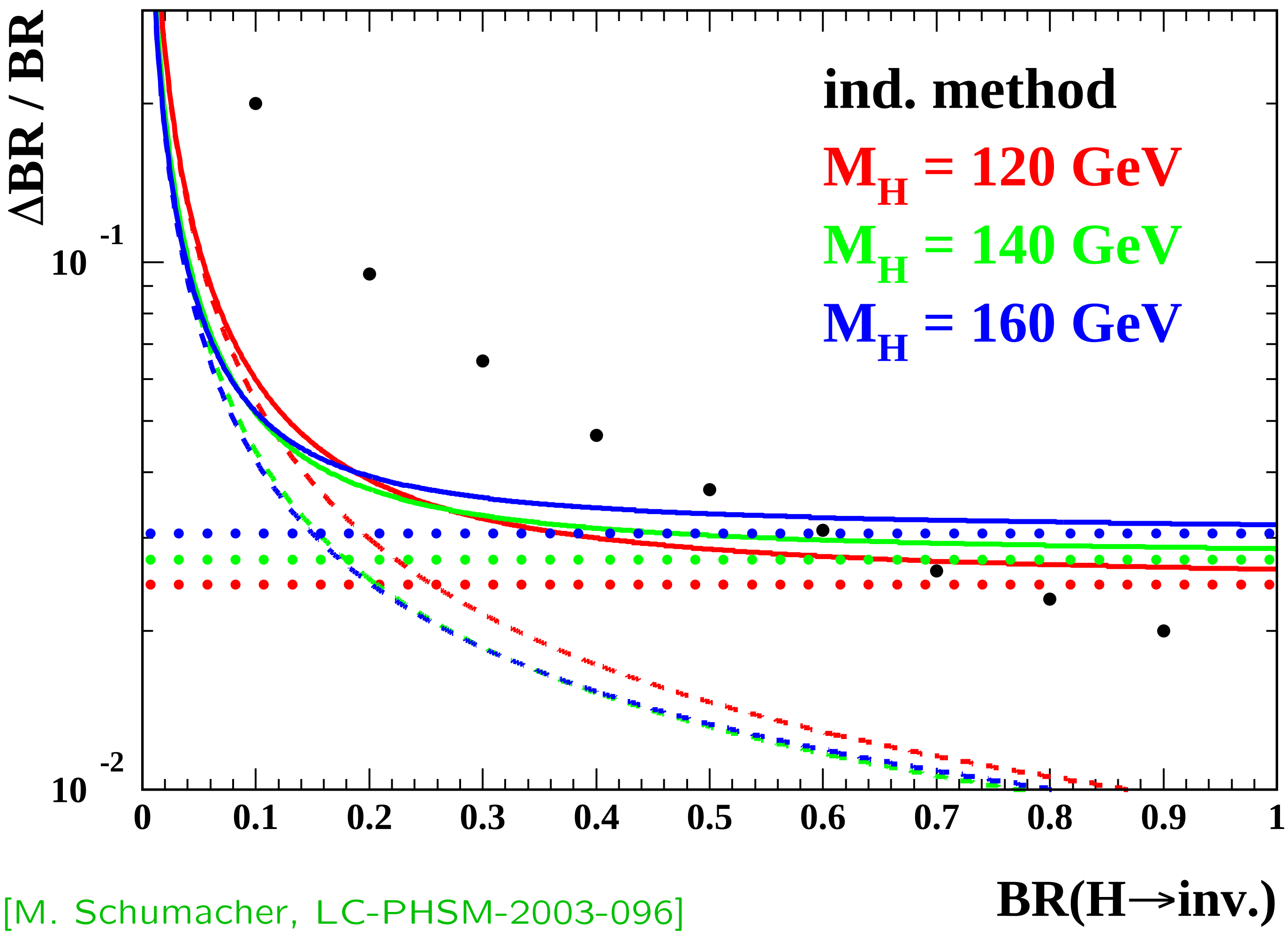
Discovery reach: 500 fb^{-1} at $\sqrt{s} = 350$ GeV

[M. Schumacher, LC-PHSM-2003-096]



5σ discovery for $\mathrm{BR_{inv}}$ down to
$\sim$ 2.5% for $m_H = 120$ GeV
$\sim$ 1.5% for $m_H = 140$, 160 GeV

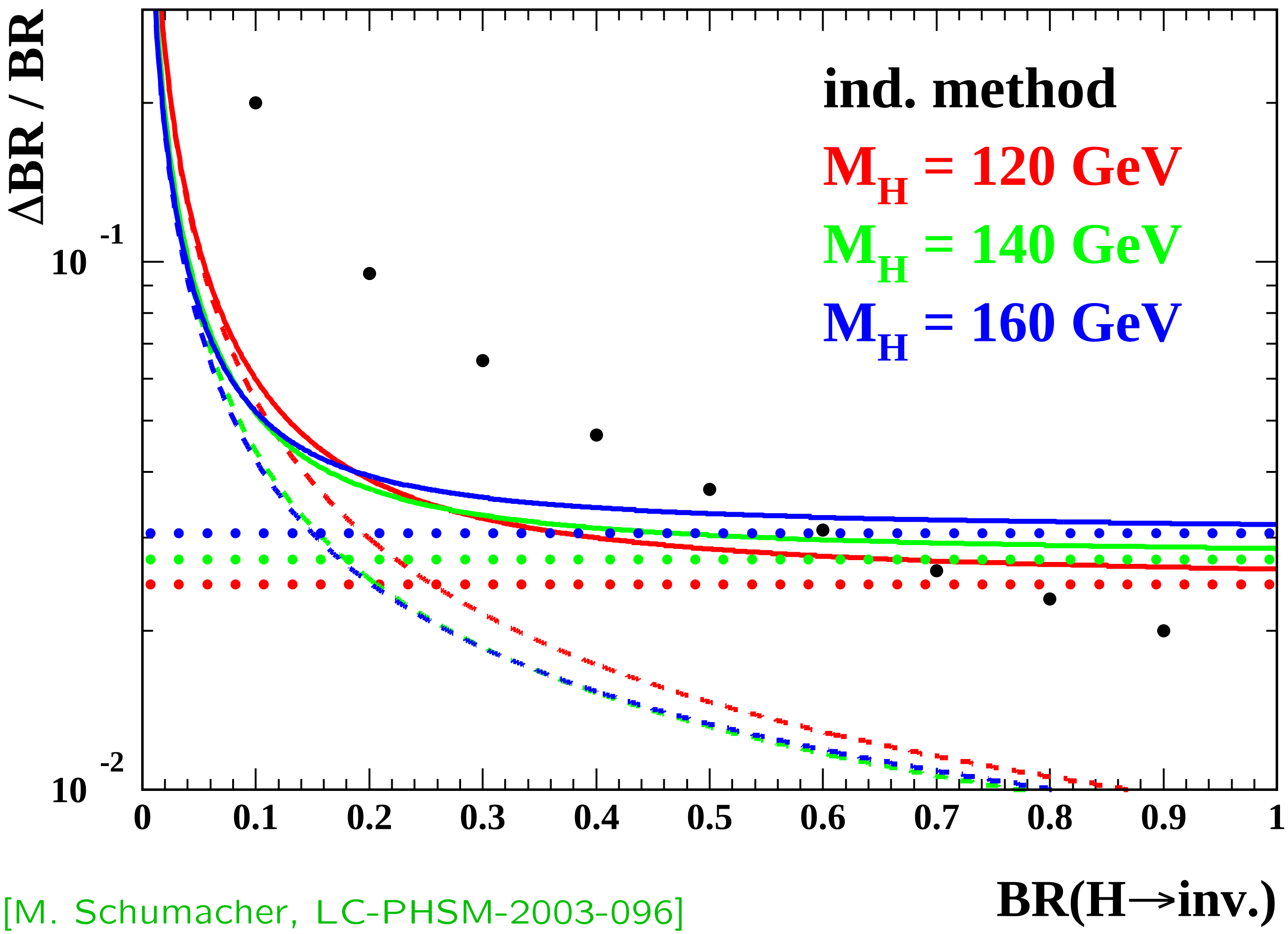
Measurement precision: $500\ \text{fb}^{-1}$ at $\sqrt{s} = 350$ GeV



[M. Schumacher, LC-PHSM-2003-096]

Precision on large BR(inv) limited by uncertainty on $\sigma(ZH)$ measurement.

Measurement precision: 500 fb^{-1} at $\sqrt{s} = 350$ GeV



[M. Schumacher, LC-PHSM-2003-096]

Indirect method:

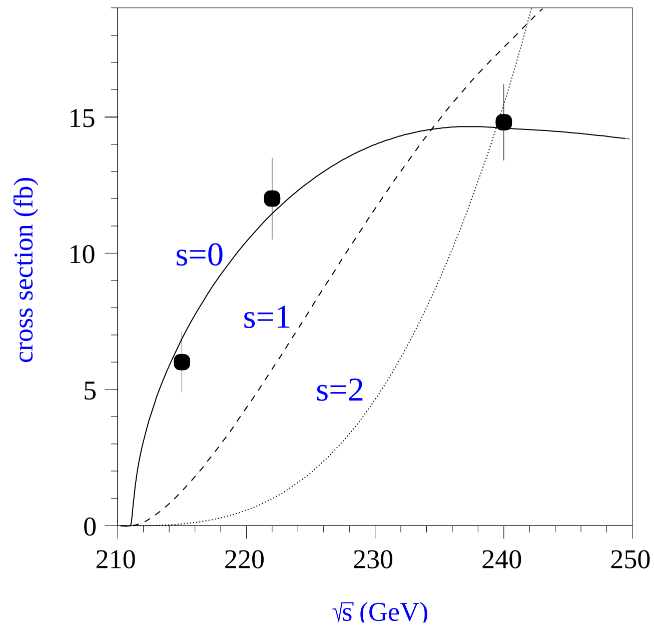
Look in recoil mass peak, count up visible final states. BR(inv) is what is left over. Better for BR(inv) $\gtrsim 0.7$.

Study: $e^+e^- \to ZH$ near threshold

[Richard & Bambade, hep-ph/0703173]

Motivation:

1) Cross section is larger near threshold.



Falls like $1/(s - m_Z^2)^2$ well above threshold due to Z propagator.

2) Better energy/momentum resolution for less-boosted visible particles: sharper Higgs recoil mass peak.

Luminosity to reach 30 MeV precision on Higgs mass for $m_H = 120$ GeV

E_{CM}	$\sigma(H\mu\mu)$ (no ISR)	Single event m_H resolution	$\mathcal{L}$ for 30 MeV ($\mu\mu + ee$)
350 GeV	4.6 fb	900 MeV	780 fb^{-1}
230 GeV	9.1 fb	200 MeV	20 fb^{-1}

[Richard & Bambade, hep-ph/0703173]

$e^+e^- \to ZH_{\text{inv}}$ with $Z \to q\bar{q}$: running near threshold

Higher cross section and less background under Higgs recoil peak.

Much less lumi needed for comparable precision.

For $m_H = 120$ GeV:

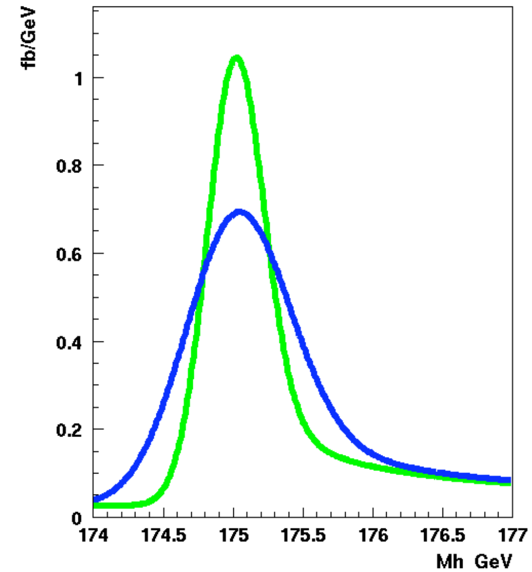
E_{CM}	$\sigma(HZ_{\text{had}})$ (34% eff)	ΔM_H (hadronic)	$Z_{\text{had}}Z_{\text{inv}}\gamma$ BG in $\pm 2\Delta m_H$	$\int \mathcal{L}$ for 95% excl of $\text{BR}_{\text{inv}} > 2\%$	$\int \mathcal{L}$ for $\text{BR}_{\text{inv}} = (2 \pm 0.5)\%$
350 GeV	30 fb	7.3 GeV	10 fb	85 fb^{-1}	500 fb^{-1}
230 GeV	60 fb	2.3 GeV	4 fb	8 fb^{-1}	50 fb^{-1}

[Richard & Bambade, hep-ph/0703173]

Better recoil mass resolution: direct access to Higgs width (!)

SM Higgs recoil spectrum,
$m_H = 175$ GeV and $\sqrt{s} = 290$ GeV.

Plotted without and with $\Gamma_H = 500$ MeV Breit-Wigner.



[Richard & Bambade, hep-ph/0703173]

Invisibly-decaying Higgs:

BR(fermions) remains measurable down to fraction of a %. Visible BR(fermions) allows ratio of partial widths between SM mode and invisible.

No BR(fermions) means $\Gamma_{\rm tot}$ larger by 2 orders of magnitude. Total width becomes measurable for $m_H = 120$ GeV!

Comparison of ILC to LHC

Higgs mass:

LHC indirect from ratio of rates. $\Delta M_H \sim$ 14–18 GeV; relies on SU(2) doublets/singlets assumption.

ILC direct from recoil spectrum. $\Delta M_H \sim$ 30 MeV; model independent.

BR(inv) discovery reach:

LHC from VBF. 5σ reach for $\xi^2 \gtrsim$ 0.65 with 30 fb^{-1}; better for 300 fb^{-1}. Maybe 0.2?

ILC from $Z(\to qq)H_{\rm inv}$. 5σ reach for $\xi^2 \gtrsim$ 0.02.

BR(inv) measurement precision:

LHC from VBF. 13% assuming cross section = SM with 30 fb^{-1}; better for 300 fb^{-1}. Maybe 4%?

ILC from indirect method. 2%, model independent.

Future directions

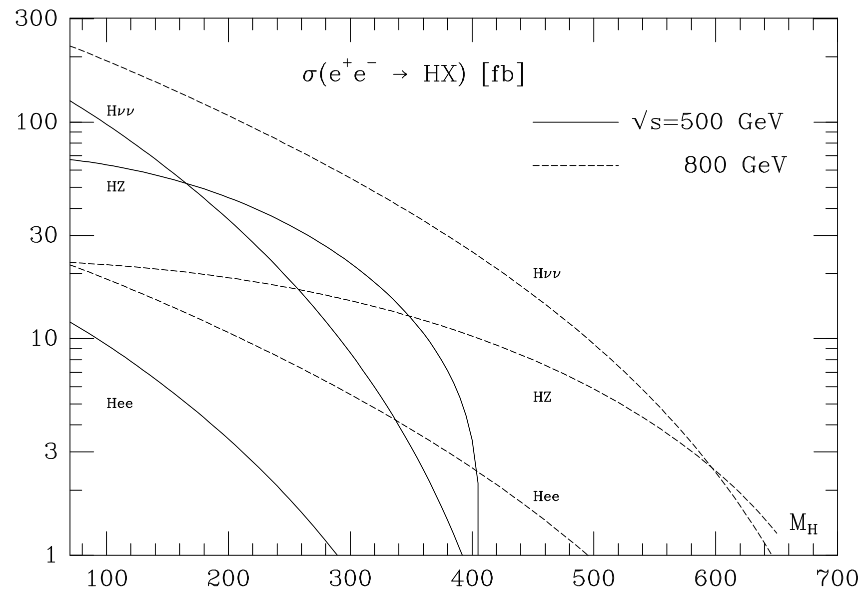
Existing ILC studies are for $\sqrt{s} = 350$ GeV and $\sqrt{s} = 230$ GeV. But if we start with 500 GeV, we won't turn it down for a while!

Should quantify how well can be done at $\sqrt{s} = 500$ GeV.
- Start with $e^+e^- \to ZH_{\rm inv}$ with $Z \to ee, \mu\mu$.
- Reconstruct recoil spectrum.
- Add ZZ fusion! Final state is $e^+e^-H_{\rm inv}$: can be used to reconstruct recoil mass.

Cross section increases with $\sqrt{s}$.

No $Z \to \ell^+\ell^-$ BR to fold in:

2x more ZZ fusion evts than $Z(\to ee, \mu\mu)H$ at $\sqrt{s} = 500$ GeV and $m_H = 120$ GeV.



- Add $Z \to q\bar{q}$ later for statistics: mass resolution is worse.
- At higher $\sqrt{s}$, add $t\bar{t}H_{\rm inv}$ for access to top Yukawa.

Backup slides

Uncertainties for LHC H_{inv} mass extraction:

Statistical uncertainty on signal rate:
$\Delta\sigma_S/\sigma_S = \sqrt{S+B}/S$

Background normalization uncertainty:
Backgrounds for $Z + H_{\text{inv}}$ and VBF are dominated by $Z \to \nu\nu$.
Can *measure* background rates/shapes in $Z \to \ell\ell$ channel!
Less statistics: $\text{BR}(Z \to \ell\ell)/\text{BR}(Z \to \nu\nu) \simeq 0.28$.
$\Delta\sigma_S/\sigma_S = \sqrt{B \times \text{BR}(\ell\ell)/\text{BR}(\nu\nu)}/S$

Theory uncertainty: QCD + PDFs
4% for VBF, 7% for $Z + h_{inv}$

Uncertainty on experimental efficiencies:
5% for VBF forward-jet tag / central-jet veto
4% dilepton tagging (2% per lepton)

Luminosity normalization: 5%